RADIATION PHYSICS NOTE 107

Estimation of Dose Equivalent Rates Resulting from Accidental Release of ^{238}U in the D0 Calorimeters

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May 1993
Revised September 1993

INTRODUCTION:

In reviewing the total amounts of depleted uranium located on the Fermilab site, DOE personnel have questioned Fermilab's classification as a non-nuclear facility. It is the primary purpose of this radiation physics note to provide a technical assessment of the estimated dose rates due to an atmospheric release of uranium from a fire in the D0 building. Direct dose rates from the uranium plates themselves, which constitute the three D0 calorimeters, have already been evaluated and are documented in reference (1).

The D0 calorimeter is divided into three separate units; the Central Calorimeter and two End Calorimeters. According to Kurt Krempetz[(2)], the Central Calorimeter contains 149 short tons of ^{238}U and each of the end calorimeters contains 60 short tons or ^{238}U. Thus the total mass of ^{238}U located at D0 would be 269 short tons or 244 metric tons. This number is somewhat higher than the official inventory number of 238 metric tons in the Depleted Uranium Inventory Database maintained by the ES&H Section, because it most likely includes the weight of the alloy plates. With the Central Calorimeter completely open, approximately 135.2E6 grams or 5.681E5 moles of ^{238}U would be exposed.

A ^{238}U fire could only occur at D0 under an extremely unlikely set of circumstances. First, all the primary safety systems and their backups[(1)] would have to fail simultaneously. Second, all monitoring systems would have to also fail simultaneously. Third, all personnel at D0 would have to ignore all alarms and physical indicators of fire. Finally the D0 calorimeters would have to be opened so that combustion could occur. There is insufficient space in the collision hall to open any of the calorimeters and there is only space enough to open one calorimeter at a time in the assembly hall. It is very improbable that any of the calorimeters at D0 would be opened in either the collision or assembly halls since this would entail a minimum interruption in the physics program of approximately 6 months.

For the purposes of this analysis I will assume that the Central Calorimeter is open exposing all 135.2 metric tons of ^{238}U to building air. I will further assume that somehow a fire is started in the ^{238}U plates, no one notices the fire, and there is no LAr or LN_2 in the near vicinity to serve as a heat sink and quenching agent. Even under all these improbable assumptions, it is unlikely that a fire in the D0 calorimeter would burn for longer than 1 hour.

CALCULATION OF PROGRAM PARAMETERS:

^{238}U Combustion Rate:

One critical factor in determining how fast a solid material will burn is its surface area to volume ratio. Large values of such ratios mean materials will burn more rapidly and lower ratios mean they will burn more slowly. Reference (3) states that a 1 inch diameter ^{238}U rod requires one day to fully burn. For an infinitely long rod of such diameter the surface area to volume ratio (**R**) would be approximately 1.575 cm^{-1}.

The ^{238}U plates at D0 were formed into either large discs or rectangular parallelepipeds.(2) All of them are 6 mm in thickness.(2) The largest discs are part of the End Calorimeters and have a diameter of 67.07" (170.4 cm) while the largest rectangular parallelepipeds are part of the Central Calorimeter and are 100" (254 cm) long and 24" (60.96 cm) wide.(2)

Surface area to volume ratios for the rectangular parallelepiped and disc respectively are approximately 3.37 cm^{-1} and 3.36 cm^{-1}. This would then imply that it would take approximately 11.2 hours for complete combustion of the ^{238}U plates, if the surface area to volume ratio of the ^{238}U plates were the dominant factor.

Another critical issue which would affect the ^{238}U combustion rate at D0 is how rapidly oxygen can be supplied to fuel a fire. A conservative estimate of the air volume within the D0 building would be 1.90E6 cubic feet. At the listed exhaust rate of 1.80E4 cubic feet/min (cfm), it would take approximately 105 minutes for a complete exchange of air in the D0 building.

There are several possible oxidation reactions for ^{238}U. I will assume that the reaction,

$$3U + 4O_2 \rightarrow U_3O_8$$

is dominant during combustion. A simple calculation shows that it requires approximately 1.70E7 liters of O_2 to fully combust the ^{238}U in the Central Calorimeter. Approximately 8.08E7 liters (2.85E6 cubic feet) of air would be needed. This is about the same amount of air as is in the entire D0 Assembly building complex. If one now assumes a 10% combustion efficiency for the oxidation of the ^{238}U and an exhaust rate of 1.8E4 ft^3/min, it would require approximately 26 hrs. to fully combust the ^{238}U. Thus the availability of oxygen would control the oxidation reaction rather than the surface area to volume ratio of the ^{238}U plates.

Particulate Velocity and ^{238}U Release Rate:

Complete combustion of the ^{238}U plates in the Central Calorimeter would produce approximately 677 Gigajoules of heat energy. Most of this energy would probably be dissipated by the stainless steel cryostat, the solid UO_2, and the other solid surrounding structures in the D0 Assembly Building since the conductivity of air is approximately 10^3 times lower that most of these substances. It is thus reasonable to assume that the average particulate velocity in the D0 exhaust stacks is primarily due to the exhaust fans. The average particulate velocity from a 30" X 30" exhaust port with a volume displacement of 1.8E4 ft^3/min is 14.8 meters/sec.

The Central Calorimeter contains approximately 45.3 Ci of ^{238}U. If this ^{238}U is fully released over a 26 hour time period, there would be 4.840E-4 Ci/sec of ^{238}U released during a fire. If one takes credit for proper operation of the automatic fire suppression system, any manual fire fighting activities, or the ability to turn off the ventilation system, this rate would drop significantly.

ATMOSPHERIC DISPERSION:

Reference (4) has provided the standard model for assessing concentrations of airborne radionuclides in air for over 20 years. This model is commonly called the gaussian plume model. The basic governing equation is:

$$\chi = \frac{Q}{2\pi\sigma_y\sigma_z\mu} \cdot e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2} \cdot \left\{ e^{-\frac{1}{2}\left[\frac{(z-H)}{\sigma_z}\right]^2} + e^{-\frac{1}{2}\left[\frac{(z+H)}{\sigma_z}\right]^2} \right\} \qquad \text{E.1}$$

where: χ = Radionuclide concentration in air at x meters downwind, y meters crosswind, and z meters above ground. (Ci/m3).

Q = Radioactivity release rate (Ci/sec.)

μ = Average ambient wind speed. Reference (5) specifies that Pasquill stability class D winds with a speed of 4.5 m/sec be used for dispersion calculations.

H = Effective plume height. For a momentum rise plume this is equal to $h + \frac{1.5 \cdot \bar{v} \cdot d}{\mu}$ where h is the stack height, $\bar{v}$ is the average particulate velocity, and d is the inner stack diameter. (m).

y = The cross wind distance. (m).

z = The vertical distance. (m).

σ_y = The horizontal dispersion coefficient. (m).

σ_z = The vertical dispersion coefficient. (m).

An average particulate velocity was estimated in a preceding section. It has also been previously assumed that the main exhaust at D0 has a 30" X 30" (0.762 m) cross section and a volume displacement rate of 1.8E4 ft^3/min. The actual height of the D0 exhaust can be estimated from the D0 ventilation system drawings as:

$$h = 774'\,3'' - 742'\,0'' = 31.25' = 9.6 \text{ m}$$

substituting the appropriate values:

$$H = 9.6 + \frac{(1.5)\cdot(14.77 \text{ m/sec})\cdot(0.762 \text{ m})}{4.5 \text{ m/sec}} = 13.35 \text{ m} \qquad \text{E.2}$$

A sector averaging technique(6) is usually applied to the basic plume dispersion equation (E.1) in computer codes such as CAP88-PC, AIRDOS-PC, and AIRDOS-EPA. When this technique is applied, the equation for ground level concentrations reduces to:

$$\chi = \frac{Q}{(0.15871)\cdot\pi\cdot x\cdot\sigma_z\cdot\mu}\, e^{-\frac{1}{2}\left(\frac{H^2}{\sigma_z^2}\right)} \qquad \text{E.3}$$

σ_z is in general a complicated function of the downwind distance x. That dependence for Pasquill stability class D winds can be approximated with the following functional form:

$$\sigma_z = (0.06 \cdot x)\cdot(1 + 0.0015 \cdot x)^{-\frac{1}{2}} \qquad \text{E.4}$$

Ground level concentrations of ^{238}U can now be calculated. Results of those calculations are presented in Table 1 and graphically displayed in Figure 1.

In the limits of large x, the function expressed as equation E.3 behaves like:

$$f(x) = K \cdot x^{-\frac{3}{2}} \cdot e^{-\frac{\alpha}{x}} \qquad \text{E.5}$$

Using standard differentiation methods from elementary calculus, it can be readily determined that the maximum for this function lies at $x = \frac{2}{3}\alpha$. The x in equation E.5 is analogous to σ_z^2 in equation E.3. Substituting into E.4 and solving for x, one obtains x = 140 meters as the only real positive root and thus the predicted approximate downwind distance at which the maximum ^{238}U concentration would occur. From Table 1 or Figure 1, it can be deduced that the maximum ^{238}U concentration actually lies somewhere around x = 170 meters.

Plume depletion due to dry deposition and precipitation has not been taken into account in generating the concentrations listed in Table 1. These effects should be very small, especially for a 1 hour time period, and they will tend to decrease the dominant immersion and inhalation doses if included. Concentrations at 30 meters from D0 are orders of magnitude below the maximum allowable workplace concentration levels specified in ref. (7), and the concentration at the site boundary (800 meters) is only an order of magnitude above those limits for a worst case accident.

DOSE EQUIVALENT RATES:

Now that the concentration of ^{238}U as a function of downwind distance during such an incident has been calculated, those concentrations must be converted into dose equivalent rates for maximally exposed individuals. In EPA and DOE approved codes, like CAP88-PC[6], this conversion is based on the following formula where it is assumed that the exposure is constant over a 1 year time period:

$$DR_{jl} = \sum_i \frac{E_{ij}(k) \cdot DF_{ijl} \cdot K_j}{P(k)} \qquad \text{E.6}$$

where:

DR = Dose equivalent rate (mrem/yr.)

$E_{ij}(k)$ = Collective exposure from i^{th} radionuclide through j^{th} pathway. (person-Ci/m^3).

DF_{ijl} = Concentration to dose equivalent rate conversion factor for i^{th} radionuclide in j^{th} pathway to l^{th} organ (mrem-cm^3/µCi-yr).

$P(k)$ = Number of exposed people at location k (person). For these calculations this number is always 1.

K_j = Conversion factor. In converting from Ci/m^3 to µCi/cm^3, this factor is 1.

Since we are only considering ^{238}U, i=1 and the sum over i in equation E.6 disappears. DF_{ijl} must be specifically calculated for the inhalation and ingestion pathways since it is usually given in mrem/pCi for these pathways. In the surface exposure and immersion pathways DF_{ijl} is usually given in mrem—cm^3/µCi-yr. Therefore the yearly dose equivalent rate can be calculated by straightforward multiplication for these pathways.

In the first few hours after its release, the dose equivalent rates from airborne ^{238}U will clearly be dominated by the inhalation pathway. Both the surface and ingestion exposure pathways are long term pathways which can be easily controlled through administrative actions and hence will not contribute to short term dose equivalents.

Due to the long half life of ^{238}U (4.5E9 yrs.), both the immersion and inhalation exposure pathways will be clearly dominated by ^{238}U concentrations for several years after any accident. This is a long enough time period for virtually all the ^{238}U to fall to the ground.

Calculation of the dose equivalent rate due to the immersion pathway involves straightforward substitutions of the ^{238}U concentration and the dose rate factor, corrected to hr^{-1} units, from tables in ref. (6) into equation E.6. Results for this pathway are listed in column 8 of Table 1. When multiplied by the number of hours the person remains in that position, these numbers give the instantaneous whole body dose equivalent received by a person standing downwind at distance x from the fire. It can be easily seen that these numbers have no measurable impact on personnel safety or health.

Calculating a dose equivalent rate for the inhalation pathway is not quite so straightforward. Tables in ref. (6) list a 50 year effective dose equivalent (also called the committed dose equivalent) factor in mrem/pCi of ^{238}U inhaled. It is assumed in ref. (6), that the standard man has a respiration rate of 9.17E5 cm^3/hr. Multiplying this by the committed dose equivalent rate factor for ^{238}U in the inhalation pathway yields 1.0775E5 mrem-cm^3/pCi-hr. Converting to μCi yields 1.078E11 mrem-cm^3/μCi-hr. Multiplying this factor by the ^{238}U concentration generates the committed dose equivalent per hour of exposure in the ^{238}U cloud. This number is listed in column 10 of Table 1.

As an example of how to use this table; suppose a person spends 2 hours at 170 meters downwind of a D0 ^{238}U fire with no respiratory protection. That person would receive 10.3 rem committed dose equivalent (2 hrs.* 5127.91117 mrem/hrs of exposure) and 5.4×10^{-6} mrem of direct dose equivalent (2 hrs. * 2.7×10^{-6} mrem/hrs. of exposure). Although these two doses are traditionally added to obtain the total dose equivalent (as in column 11) it should be noted that virtually all of the dose equivalent is integrated over a 50 year period. Hence the average annual dose to the individual receiving 10.3 rem committed dose equivalent, is 206 mrem per year.

SUMMARY:

The possibility of a fire at D0 is extremely remote. Should such a fire occur, the only measurable dose equivalent rates to individuals would come from the inhalation pathway. Individuals standing approximately 170 meters downwind of a D0 fire for 1 hour, could receive a committed dose equivalent of as much as 5.1 rem (103 mrem/yr. average annual dose equivalent). Appropriate administrative controls could reduce to 0 the possibility of personnel outside the D0 building receiving committed dose equivalents exceeding 100 mrem. Firemen and building personnel could easily be protected with the appropriate respirators.

A person's committed dose equivalent at the nearest site boundary (SSW of D0) could be as high as 825 mrem/hr. of exposure under the conditions modeled in this note.

REFERENCES

(1) Paul D. Grannis, Roger Dixon, H. Eugene Fisk, A. Lincoln Read, and Larry D. Spires, Fermilab D-Zero Detector (E-740) Safety Assessment Document, Fermi National Accelerator Laboratory, Fermilab Research Division D-Zero Construction Department, May 20, 1992.

(2) Phone conversation between Kurt Krempetz of the D0 staff and Vernon Cupps of the ES&H Section staff, 2/23/93.

(3) Fire Protection Handbook, National Fire Protection Association, 17th Edition, 1990.

(4) Meteorology and Atomic Energy, David H. Slade, Editor, U.S. Atomic Energy Commission Office of Information Services, July 1968.

(5) Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports, DOE-STD-1027-92, U.S. Department of Energy, Washington, DC, 20585, December 1992.

(6) Barry S. Parks, Users Guide for CAP88-PC, Version 1.0, USEPA, Las Vegas, NV, 89193-8517, March 1992.

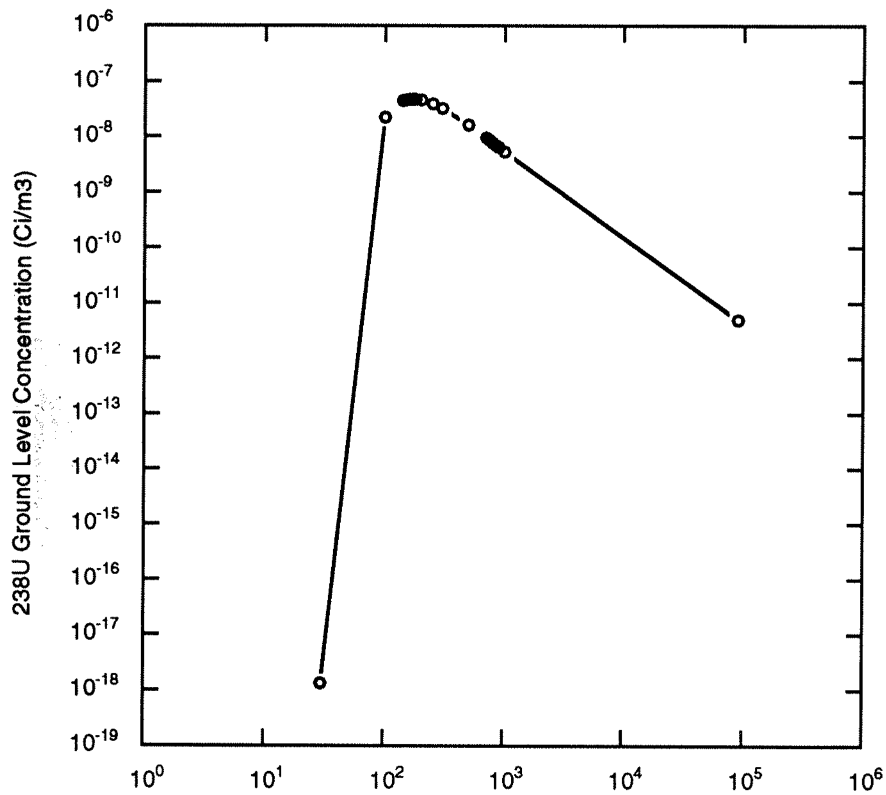
(7) Safety Procedures for Processing Depleted Uranium, DARCOM Handbook 385-1.1-78, HQ, US Army Material Development and Readiness Command, 8/78.

TABLE 1-9/93

Downwind distance x (m)	Average Release Rate Q (Ci/sec)	Average Stack Gas Velocity (m/sec)	Effective Stack Height H (m)	Vertical Dispersion Coefficient (m)	238U Ground Level Concentration (Ci/m3)	Immersion Dose Rate Factor (mrem-cm3/uCi-hr.)	Immersion Dose Equivalent Rate (mrem/hr)	Inhalation Committed Dose Rate Factor (mrem-cm3/uCi-hr)	Inhalation Committed Dose Equivalent Rate (mrem/hr of exposure)	Total Committed Dose Equivalent Rate (mrem/hr of exposure)
30	4.84E-04	4.5	13.35	1.76	1.3108E-18	5.77E+01	7.5632E-17	1.08E+11	1.413E-07	1.413E-07
100	4.84E-04	4.5	13.35	5.595	2.2377E-08	5.77E+01	1.2911E-06	1.08E+11	2412.22511	2412.22512
141	4.84E-04	4.5	13.35	7.708	4.4293E-08	5.77E+01	2.5557E-06	1.08E+11	4774.83179	4774.83179
150	4.84E-04	4.5	13.35	8.132	4.5959E-08	5.77E+01	2.6518E-06	1.08E+11	4954.32871	4954.32871
160	4.84E-04	4.5	13.35	8.621	4.715E-08	5.77E+01	2.7206E-06	1.08E+11	5082.8001	5082.8001
170	4.84E-04	4.5	13.35	9.105	4.7569E-08	5.77E+01	2.7447E-06	1.08E+11	5127.91117	5127.91117
175	4.84E-04	4.5	13.35	9.345	4.7545E-08	5.77E+01	2.7433E-06	1.08E+11	5125.33704	5125.33704
180	4.84E-04	4.5	13.35	9.583	4.739E-08	5.77E+01	2.7344E-06	1.08E+11	5108.63247	5108.63247
200	4.84E-04	4.5	13.35	10.52	4.5829E-08	5.77E+01	2.6443E-06	1.08E+11	4940.37537	4940.37538
250	4.84E-04	4.5	13.35	12.79	3.9128E-08	5.77E+01	2.2577E-06	1.08E+11	4218.01482	4218.01482
300	4.84E-04	4.5	13.35	14.95	3.2282E-08	5.77E+01	1.8627E-06	1.08E+11	3480.00766	3480.00766
500	4.84E-04	4.5	13.35	22.68	1.5997E-08	5.77E+01	9.2301E-07	1.08E+11	1724.43762	1724.43762
700	4.84E-04	4.5	13.35	29.33	9.4729E-09	5.77E+01	5.4658E-07	1.08E+11	1021.17395	1021.17395
750	4.84E-04	4.5	13.35	30.87	8.4854E-09	5.77E+01	4.896E-07	1.08E+11	914.720757	914.720758
800	4.84E-04	4.5	13.35	32.36	7.6528E-09	5.77E+01	4.4157E-07	1.08E+11	824.976644	824.976645
850	4.84E-04	4.5	13.35	33.81	6.9432E-09	5.77E+01	4.0062E-07	1.08E+11	748.476267	748.476268
900	4.84E-04	4.5	13.35	35.23	6.332E-09	5.77E+01	3.6536E-07	1.08E+11	682.591941	682.591941
1000	4.84E-04	4.5	13.35	37.95	5.3431E-09	5.77E+01	3.083E-07	1.08E+11	575.988819	575.988819
9.14E+04	4.84E-04	4.5	13.35	470	5.0195E-12	5.77E+01	2.8962E-10	1.08E+11	0.54110079	0.54110079

FIGURE 1

Ground Level Concentration of Airborne 238U as a function SSW Distance from D0



Distance from D0 in the SSW direction (meters)